NASA TECHNICAL NOTE

N73-16498
NASA TN D-7129

NASA TN D-7129

FIRST-ORDER OPTICAL ANALYSIS OF A QUASI-MICROSCOPE FOR PLANETARY LANDERS

by Friedrich O. Huck, Archibald R. Sinclair, and Ernest E. Burcher

Langley Research Center
Hampton, Va. 23365

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1973

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-7129		
4. Title and Subtitle FIRST-ORDER OPTICAL ANALYSIS OF A QUASI-MICROSCOPE FOR PLANETARY LANDERS		5. Report Date February 1973
		6. Performing Organization Code
7. Author(s) Friedrich O. Huck, Archibald R. Sinclair, and Ernest E. Burcher		8. Performing Organization Report No. L-8527
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 502-03-52-04
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A first-order geometrical optics analysis of a facsimile camera augmented with an auxiliary lens as magnifier is presented. This concept, called quasi-microscope, bridges the gap between surface resolutions of the order of 1 to 10 mm which can be obtained directly with planetary lander cameras and resolutions of the order of 0.2 to 10 μm which can be obtained only with relatively complex microscopes. A facsimile camera is considered in the analysis; however, the analytical results can also be applied to television and film cameras.

It is found that quasi-microscope resolutions in the range from 10 to 100 μm are obtainable with current state-of-the-art lander facsimile cameras. For the Viking lander camera having an angular resolution of 0.04°, which is considered herein as a specific example, the best achievable resolution would be about 20 μm. The preferred approach to increase the resolution of the quasi-microscope would be, if possible, through an increase in angular resolution of the camera. A twofold to threefold improvement in resolution could also be achieved with a special camera focus position, but this approach tends to require larger and heavier auxiliary optics.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Facsimile camera Planetary lander Microscope	Unclassified – Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	28	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

FIRST-ORDER OPTICAL ANALYSIS OF A QUASI-MICROSCOPE FOR PLANETARY LANDERS

By Friedrich O. Huck, Archibald R. Sinclair,
and Ernest E. Burcher
Langley Research Center

SUMMARY

A first-order geometrical optics analysis of a facsimile camera augmented with an auxiliary lens as magnifier is presented. This concept, called quasi-microscope, bridges the gap between surface resolutions of the order of 1 to 10 mm which can be obtained directly with planetary lander cameras and resolutions of the order of 0.2 to 10 μm which can be obtained only with relatively complex microscopes. A facsimile camera is considered in the analysis; however, the analytical results can also be applied to television and film cameras.

It is found that quasi-microscope resolutions in the range from 10 to 100 μm are obtainable with current state-of-the-art lander facsimile cameras. For the Viking lander camera having an angular resolution of 0.04°, which is considered herein as a specific example, the best achievable resolution would be about 20 μm. The preferred approach to increase the resolution of the quasi-microscope would be, if possible, through an increase in angular resolution of the camera. A twofold to threefold improvement in resolution could also be achieved with a special camera focus position, but this approach tends to require larger and heavier auxiliary optics.

INTRODUCTION

Visual imaging of the terrain surrounding a lunar or planetary lander is generally accepted to be of primary importance, as is amply demonstrated by the U.S.S.R. Luna (refs. 1 and 2) and Lunakhod (ref. 3) and the U.S.A. Surveyor (ref. 4) and Viking (ref. 5) spacecraft. Surface resolutions obtainable with the imaging systems on these spacecraft have been limited to about 1 to 10 mm, although higher resolutions would have been very desirable. The scientific value of obtaining a 10-μm resolution from lander missions to Mars, for example, has been particularly stressed by the Space Science Board on Planetary Exploration (ref. 6). However, because of the wide depth of field requirements, significant improvements in lander camera resolution are difficult to achieve (ref. 7).

Microscopes with resolutions in the range from 0.2 to 10 μm have been investigated and proposed for planetary missions (refs. 8, 9, and 10). Such instruments could gather extremely valuable scientific data but would require very complex designs, especially when multiple sample preparation and high resolutions are to be obtained.

To bridge the gap between the high resolutions which can be obtained only with complex microscope designs and the relatively low surface resolutions which can be obtained with current state-of-the-art lander cameras, a quasi-microscope concept is introduced. The quasi-microscope consists of a lander camera augmented with a simple optical device used as a magnifier. The auxiliary optics are not allowed to constrain the normal operation of the camera in surveying the surrounding terrain and are required only to be within view of the camera.

This paper presents a first-order geometrical optics analysis of the basic performance capabilities and limitations of such a quasi-microscope and some photographs to demonstrate the validity of this concept. A facsimile camera is considered in the analysis; however, the analytical results can be directly applied to television and film cameras by defining an effective instantaneous field of view, or angular resolution, for these devices analogous to that of the facsimile camera.

SYMBOLS

A	quasi-microscope object area, m^2
c	distance between auxiliary lens and camera lens, m
D	lens diameter, m
d_a	diameter of quasi-microscope picture element, or quasi-microscope resolution, m
d_c	diameter of camera photosensor pinhole, m
f	lens focal length, m
k	distance between camera lens and scanning mirror, m
ℓ	distance from lens, m
$\Delta\ell$	depth of field or focus, m

m_ℓ	longitudinal magnification
m_t	transverse magnification
β	instantaneous field of view of camera, rad or deg
θ	angular diameter of first dark ring in camera lens diffraction pattern, rad or deg
λ	wavelength, m
Ω	number of unvignetted pixels per line scan across center of auxiliary lens
ω	angle which camera mirror can scan across center of auxiliary lens without vignetting, deg or rad

Subscripts:

a	auxiliary lens
c	camera lens
i	virtual image
p	primary
s	secondary

Prime with a symbol indicates that $\ell_a = f_a$ and $\ell_c = f_c$.

ANALYSIS

The purpose of this section is to review briefly optical properties of the facsimile camera and then to formulate optical properties of the facsimile camera augmented with an auxiliary lens as magnifier, that is, of the quasi-microscope. Only first-order geometrical optics are considered.

Optical Properties of the Facsimile Camera

The facsimile camera consists basically of a radiometer and a scanning mechanism, as is illustrated in figure 1. The objective lens of the radiometer captures light and

transmits it through a pinhole to a photosensor which transduces it into an electrical signal. To image a scene, the scanning mechanism generates vertical line scans by a nodding or rotating mirror and provides proper spacing between successive line scans by rotating the line-scan and radiometer assembly in azimuth.

The two performance parameters of the facsimile camera important to this analysis are instantaneous field of view, or angular resolution, expressed as

$$\beta = 2 \tan^{-1} \frac{d_c}{2\ell_c} \approx \frac{d_c}{\ell_c} \tag{1}$$

and depth of focus (ref. 7) given by

$$\Delta\ell_c = \frac{2\ell_c d_c}{D_c\left[1 - \left(\frac{d_c}{D_c}\right)^2\right]} \approx 2\ell_c \frac{d_c}{D_c} \tag{2}$$

For these relations to be valid, the effect of diffraction by the lens must be small. This condition is assured if, for a diffraction-limited lens, the angular diameter θ of the first dark ring in the diffraction pattern is smaller than the instantaneous field of view β, that is, if

$$\beta > \theta = \frac{2.44\lambda}{D_c} \tag{3}$$

where λ is the longest wavelength to which the camera photosensor responds.

Since lander cameras are generally required to image from 1 or 2 m to infinity, the focus positions of the pinholes are located so that $\ell_c \geqq f_c$. Whether one or several focus positions are required depends on the instantaneous field of view or angular resolution, lens diameter, and depth of field. A performance analysis of the facsimile camera (ref. 7) has shown that current state-of-the art in solid-state photosensor/preamplifier designs generally limits the camera angular resolution to about 0.1° for a single focus position and to about 0.02° for multiple, fixed focus positions (the Viking lander camera, for example, has an angular resolution of 0.04° and four focus steps).

Optical Properties of the Quasi-Microscope

A basic quasi-microscope system is shown in figure 2. The auxiliary lens is located remotely from the facsimile camera and performs the function of a magnifier. The sample

to be imaged is placed on the object side of the auxiliary lens, and the facsimile camera images the virtual image.

The geometrical performance parameters which describe important properties of the quasi-microscope are transverse and longitudinal magnification, resolution, depth of field, and number of unvignetted picture elements (pixels). Object area is included for completeness. Details of derivations are given in the appendix; only the more important analytical expressions are presented here.

Transverse and longitudinal magnification.- The transverse magnification of the combined auxiliary lens and camera lens is

$$m_t = \frac{f_c\left(c - f_a\right) - \ell_c\left(c - f_a - f_c\right)}{f_a f_c} \tag{4a}$$

$$m_t = \frac{f_a f_c}{f_a\left(c - f_c\right) - \ell_a\left(c - f_a - f_c\right)} \tag{4b}$$

For the special case when the object is placed at the focal distance of the auxiliary lens $\left(\ell_a = f_a\right)$ and the facsimile camera is focused at or near infinity $\left(\ell_c \approx f_c\right)$, equations (4) reduce to

$$m_t' = \frac{f_c}{f_a} \tag{5}$$

The longitudinal magnification is given by

$$m_\ell = m_t^2 = \frac{f_c\left(c - f_a\right) - \ell_c\left(c - f_a - f_c\right)}{f_a\left(c - f_c\right) - \ell_a\left(c - f_a - f_c\right)} \tag{6}$$

Resolution.- By the definition of transverse magnification, the resolution of the quasi-microscope may be written

$$d_a = \frac{d_c}{m_t} \tag{7}$$

where m_t is given by equations (4). For the special case when $\ell_a = f_a$ and $\ell_c = f_c$, then $m_t = m_t'$ (eq. (5)), $d_c = \beta f_c$, and equation (7) becomes

$$d_a' = \frac{f_c \beta}{m_t'} = \beta f_a \tag{8}$$

It may be of interest to know the increase in resolution achieved with the auxiliary lens over the resolution obtained without the lens. This increase may be given by the magnifying power MP of the auxiliary lens which is defined as the ratio of the angle subtended by the auxiliary lens image at the facsimile camera to the angle subtended by the object, or

$$MP = \frac{f_a\left(\ell_a + c\right)}{f_a\left(\ell_a + c\right) - \ell_a c} \tag{9}$$

For the special case when $f_a = \ell_a$,

$$MP' = \frac{f_c + c}{f_a} \tag{10}$$

Depth of field.- For a camera depth of focus $\Delta\ell_c$, the depth of field of the quasi-microscope $\Delta\ell_a$ becomes from the definition of longitudinal magnification

$$\Delta\ell_a = \frac{\Delta\ell_c}{m_\ell} \tag{11}$$

where $\Delta\ell_c$ is given by equation (2) and m_ℓ is given by equation (6).

For the special case when $\ell_a = f_a$ and $\ell_c = f_c$, the depth of field becomes

$$\Delta\ell_a' = \frac{2\beta}{D_c} f_a^2 \tag{12}$$

Number of unvignetted pixels.- Since the auxiliary lens forms an out-of-focus field stop, the edge of the field of view is vignetted. The angle ω (in rad) which the camera mirror can scan through the center of the auxiliary lens without vignetting is obtained from the following equation:

$$\omega = \frac{D_a - \dfrac{D_c}{1 + c\,\dfrac{f_a - \ell_a}{\ell_a f_a}}}{c - k} \tag{13}$$

where k is the distance from camera lens to scanning mirror. Generally, $c \gg k$, and k can be neglected. For the special case when $\ell_a = f_a$,

$$\omega' = \frac{D_a - D_c}{c} \tag{14}$$

For an instantaneous field of view β, the total number of unvignetted pixels per line scan through the center of the auxiliary lens is

$$\Omega = \frac{\omega}{\beta} \tag{15}$$

and the total number of unvignetted pixels per frame is $\frac{\pi}{4}\,\Omega^2$.

Object area.- Knowledge of the object area is required to determine the necessary illumination for the sample. On the basis of the foregoing results, the object area which needs to be evenly illuminated is

$$A = \frac{\pi}{4}\left(\frac{\omega}{m_t}\right)^2 \tag{16}$$

where ω is given by equation (13) and m_t is given by equations (4).

EVALUATION OF ANALYTICAL RESULTS

The results presented in the analysis are now evaluated. The evaluation is presented in three parts. First, the transverse magnification is explored to gain a general insight into the performance of the quasi-microscope as a function of camera design, auxiliary lens parameters, and distance between camera lens and auxiliary lens. Second, quasi-microscope designs which do not impose special requirements on the camera design are examined in more detail. The Viking lander camera is considered as a specific example. Finally, this constraint is lifted and quasi-microscope designs which impose special requirements on the camera design are further investigated.

Transverse Magnification

In order to investigate the effect of camera focus position and auxiliary lens location, it is convenient to rewrite the expression for the transverse magnification given by equations (4) in the form

$$m_t = \frac{m_t'}{f_c}\left(1 - \frac{\ell_c}{f_c}\right)c + \frac{\ell_c}{f_c}\left(1 + m_t'\right) - 1$$

The parameter m_t' (eq. (5)) is the transverse magnification when $\ell_c = f_c$.

Figure 3 presents variations of m_t with the distance between the camera lens and auxiliary lens c and with ℓ_c/f_c, where ℓ_c is the distance between the camera lens and detector pinhole and f_c is the camera lens focal length. Assumed are $f_c = 9$ cm and $f_a = 3$ cm; hence, $m_t' = \frac{f_c}{f_a} = 3$.

If the auxiliary lens is not allowed to obstruct the general field of view of the camera, then the distance c between the camera lens and auxiliary lens must generally be larger than about 20 cm, and hence larger than the sum of the focal lengths of the two lenses (i.e., $c > f_a + f_c$). Under this constraint, several conclusions about the quasi-microscope can be drawn, as follows:

(1) When $\frac{\ell_c}{f_c} > 1$, m_t increases as c decreases.

(2) When $\frac{\ell_c}{f_c} = 1$, m_t is independent of c.

(3) When $\frac{\ell_c}{f_c} < 1$, m_t increases as c increases.

(4) The transverse magnification m_t is higher for $\frac{\ell_c}{f_c} < 1$ than for $\frac{\ell_c}{f_c} > 1$.

Facsimile cameras are generally designed to image from 1 or 2 m to infinity, so that $\frac{\ell_c}{f_c} \geqq 1$. This case is discussed in detail in the next section. Since considerably higher transverse magnifications are possible when $\frac{\ell_c}{f_c} < 1$ (which would impose an additional focus requirement on the facsimile camera design), this case is further examined in a subsequent section.

Quasi-Microscope Designs Which do not Impose a Focus Requirement on Facsimile Camera Designs

As previously noted, quasi-microscope designs do not impose a special focus requirement on facsimile camera designs when $\frac{\ell_c}{f_c} \geqq 1$. It follows from figure 3 that

best resolution can then be achieved when $\ell_c = f_c$, and consequently when $\ell_a = f_a$. Actually, facsimile cameras are generally not required to focus exactly at infinity but contain infinity within their depth of field. This is, for example, true for the Viking lander camera (ref. 5). However, as will be illustrated, the resultant effect on quasi-microscope performance is generally small.

Inspection of equation (8) reveals that best quasi-microscope resolution is achieved when the focal length of the auxiliary lens f_a is small, and inspection of equation (14) reveals that the maximum number of unvignetted pixels is obtained when the diameter of this lens D_a is large. It is, therefore, desirable that the auxiliary lens focal ratio f_a/D_a be small. It is assumed herein that lenses with focal ratios as small as unity are available for the required magnifying function without grave distortions. (This assumption was confirmed by tests which are described later.)

The performance of the quasi-microscope under these conditions is plotted in figure 4. The left vertical axes of these performance curves are given in terms of the instantaneous field of view β, lens diameter of the facsimile camera D_c, and the distance between the camera lens and auxiliary lens c. The right vertical axes are given in terms of the high-resolution imaging mode of the Viking lander camera and a distance between the auxiliary lens and camera lens c of 100 cm.

Pertinent Viking lander camera design characteristics (from ref. 5) are as follows:

Instantaneous field of view, β	0.04°
Objective lens diameter, D_c	0.95 cm
Objective lens focal length, f_c	5.3 cm
Far field focus position	13.3 m

The results shown in figure 4 assume that $\ell_a = f_a$ and $\ell_c = f_c$, whereas generally $\ell_c > f_c$. That the resulting discrepancy may often be small is illustrated for the Viking lander camera. One of the four focus steps of this camera is focused at a distance of 13.3 m and includes infinity as one extreme of the depth of field. For the camera lens focal length f_c of 5.3 cm, the pinhole distance from the lens ℓ_c is 5.321 cm. Equating equations (4a) and (4b) gives the proper distance between object and auxiliary lens as a function of ℓ_c as

$$\ell_a = \frac{1}{c - f_a - f_c}\left[f_a\left(c - f_c\right) - \frac{f_a^2 f_c^2}{f_c\left(c - f_a\right) - \ell_c\left(c - f_a - f_c\right)}\right]$$

Assuming, for example, in the foregoing equation that $f_a = 3$ cm results in $\ell_a = 2.993$ cm. Using equations (4) gives $m_t = 1.649$, and using equation (7) gives

$d_a = 22.5\ \mu m$. This value of d_a is very close to $d'_a = 21\ \mu m$ obtained under the assumption that $\ell_a = f_a$ and $\ell_c = f_c$. It is clear from figure 3 that this discrepancy would decrease for smaller values of c and increase for larger values.

Two general observations can be made from these results:

First, it is desirable to place the auxiliary lens as close as possible to the camera since the number of pixels is inversely proportional to the distance c.

Second, if the choice is available, it is preferable to achieve high resolution by the use of a narrow camera instantaneous field of view β rather than by the use of a small auxiliary lens focal length f_a. The reason is twofold: (1) The number of unvignetted pixels can be increased both by narrowing β and by widening D_a $\left(\approx f_a\right)$. (2) The depth of field $\Delta\ell'_a$ can be increased, since $\Delta\ell'_a$ is linearly proportional to β, but as the square to f_a.

Specific results for the Viking lander camera show that the best realizable quasi-microscope resolution with this camera is about 20 μm, using a $f_a = D_a = 3$ cm auxiliary lens. Since the best resolution otherwise obtainable with this camera is 1.2 mm (at a distance of 1.7 m), resolution has been increased by a factor of 60. The corresponding depth of field is 120 μm. The auxiliary lens should be placed as close as possible to the camera to assure that a sufficient number of pixels is obtained. At a distance of 50 cm, for example, 56 pixels per line would be obtained through the center of the auxiliary lens, or about 2460 pixels per frame.

Quasi-Microscope Designs Which Impose a Special Focus Requirement on Facsimile Camera Designs

The transverse magnification of the quasi-microscope can be increased by allowing ℓ_c/f_c to be less than 1 and, consequently, by imposing special focus requirements on facsimile camera designs. The Viking lander camera objective lens parameters and instantaneous field of view are considered herein as a specific example; otherwise, the camera itself is assumed to have a complete freedom of focusing.

Plotted in figure 5 are the variations of quasi-microscope depth of field (as given by eq. (11)) and number of unvignetted pixels per line scan across the center of the auxiliary lens (eqs. (13) and (15)) with resolution (eq. (7)). The performance characteristics of the quasi-microscope are illustrated in figure 5(a) for $\beta = 0.04^{\circ}$ and $c = 100$ cm, in figure 5(b) for $\beta = 0.04^{\circ}$ and $c = 50$ cm, and in figure 5(c) for $\beta = 0.02^{\circ}$ and $c = 50$ cm. These curves show that improvements in resolution and an increase in number of unvignetted pixels can be gained with a special camera focus position, approximately a factor of 2 to 3 either in resolution or in number of unvignetted pixels per line scan. However, to gain this improvement requires, in addition to the extra camera focus position, a longer

focal length auxiliary lens. Since the auxiliary lens diameter is assumed to be equal to the focal length, this requirement would result in the use of physically larger, and hence heavier, lenses.

AUXILIARY LENS TESTS

The analysis revealed that very low focal-ratio auxiliary lenses are required to obtain high quasi-microscope resolutions, and the analytical results assumed focal ratios equal to unity. The purpose of this section is to demonstrate that readily available lenses with low focal ratios, although not specifically designed for this purpose, can operate in the required quasi-microscope mode without excessive aberrations. Since only the performance of the auxiliary lens and objective lens configuration is of interest, it is advantageous to use a film camera with a high-resolution film rather than a facsimile camera which would yield a lower resolution. The effect of the facsimile camera photosensor aperture and line-scan process on the resultant image has been analyzed elsewhere (ref. 11) and is not an important factor in this investigation.

The objective lens of the film camera was selected to be similar to that of the Viking lander camera and has a focal length f_c of 5.1 cm and an aperture diameter D_c of 0.91 cm. Two auxiliary lenses are investigated. Both lenses have a focal ratio of 0.78; one lens has a focal length f_a of 2.5 cm ($D_a = 3.2$ cm) and the other, 6.5 cm ($D_a = 8.3$ cm). Together, these two focal lengths cover the more important part of the range of focal length encompassed by the analytical results.

The experimental setup of film camera, auxiliary lens, and test target is shown in figure 6. The distance between the camera lens and auxiliary lens is maintained at 100 cm for all tests. The two test targets are shown in figure 7. Regular patterns were used so that aberrations would readily be revealed. The dot pattern target was selected because the size of detail was convenient for the range of resolutions obtained with the two lenses. The screen target was selected because the width of the screen lines is 10 μm which is about the highest resolution practical for this quasi-microscope concept.

Quasi-microscope images obtained with the 2.5-cm and 6.5-cm focal length auxiliary lenses are shown in figures 8 and 9, respectively. In figures 8(a), 8(b), and 9(a), the targets are placed at the focal point of the auxiliary lens ($\ell_a = f_a$) and the camera is focused at infinity ($\ell_c = f_c$). This configuration represents the condition which does not impose any special focus requirements on lander camera designs. The condition which does impose a special focus requirement on lander camera designs is shown in figure 9(b). The target is placed for this test 0.3 cm beyond the focal point of the auxiliary lens ($\ell_a = 6.8$ cm) and the camera is focused beyond infinity ($\ell_c < f_c$).

These photographs demonstrate that the analytically predicted resolutions for the quasi-microscope concept are achievable. All the photographs show a decrease in resolution and contrast toward the edges of the image due to vignetting (as was predicted by the first-order geometrical optics analysis) and off-axis aberrations. Furthermore, figure 9(b) reveals that blurring and distortions caused by aberrations, as well as vignetting, increase significantly when resolution is increased by moving the target beyond the focal point of the auxiliary lens.

A logical follow-on investigation would be to predict the extent to which aberrations can be reduced in auxiliary lenses specifically designed for the quasi-microscope concept. Such a prediction would require a third-order geometrical optics analysis which is beyond the scope of this paper.

CONCLUDING REMARKS

A first-order geometrical optics analysis was presented of the performance achievable with a facsimile camera augmented with an auxiliary lens as magnifier, an arrangement called quasi-microscope. The performance parameters of importance were resolution, depth of field, and number of unvignetted picture elements (pixels). Quasi-microscope images of test targets were also presented to demonstrate the validity of assumptions made to obtain analytical results.

Results of the analysis led to the following general conclusions:

1. Quasi-microscope resolutions ranging between 10 to 100 μm are obtainable with current state-of-the-art facsimile cameras.

2. It is always advantageous to use an auxiliary lens with a small focal ratio and to place this lens as close as possible to the camera.

3. The most attractive approach to increase the quasi-microscope performance is, if possible, through an increase in the angular resolution of the facsimile camera. Increase in angular camera resolution by a certain factor increases both the quasi-microscope resolution and the number of pixels per line scan by the same factor. However, the depth of field is also decreased by this factor.

4. A twofold to threefold improvement in either resolution or number of unvignetted pixels per line scan can be achieved by use of a special focus position (focus beyond infinity) in the facsimile camera. However, this approach tends to require larger and heavier auxiliary lenses.

As a specific example, it was found that the best achievable resolution with the Viking lander camera having an angular resolution of 0.04° would be about 20 μm, but with a very small number of unvignetted pixels. A more practical resolution would be

40 μm with a 6-cm focal length auxiliary lens. The corresponding depth of field would be 500 μm, and the total number of unvignetted pixels per frame would be 15 400 for a distance between camera and auxiliary lens of 50 cm.

Experimental results obtained with two readily available low focal-ratio (f/0.78) lenses as magnifiers revealed some blurring and distortion toward the edge of the image due to off-axis aberrations of the auxiliary lens, in addition to the vignetting predicted by the first-order geometrical optics analysis. This blurring and distortion increased significantly when an increase in resolution was sought by use of a special camera focus position. A third-order geometrical optics analysis would be required to predict more accurately the performance and requirements of auxiliary lenses specifically designed for this quasi-microscope concept.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 15, 1973.

APPENDIX

SINGLE-LENS EQUIVALENT FOR QUASI-MICROSCOPE

Performance equations for the quasi-microscope are most conveniently derived by using a single-lens equivalent of the auxiliary lens and camera lens. To construct a single-lens equivalent, it must be assumed that both the auxiliary lens and camera lens are positioned normal to a common optical center line. This condition is not strictly true since the image is formed by a scanning mirror located between the two lenses. However, the angle over which the magnified image is scanned is very small and any errors are therefore also small and are neglected. The geometrical relationships necessary for constructing a single-lens equivalent for two thin lenses, as illustrated in figure 10, are presented in several publications (see, for example, ref. 12). The derivation of these relationships is performed in this appendix for convenient reference.

Shown in figure 11(a) is the geometry for constructing the primary and secondary principal planes, PPP and SPP, and for determining the primary and secondary focal points, F_p and F_s. From an arbitrarily selected point 1 on the left side of the auxiliary lens, a ray is drawn to point 2, parallel to the optical axis. The auxiliary lens refracts the ray through its focal point to point 3. Then the camera lens refracts the ray through point 4 toward the optical axis. Point 4 is the intersection of the camera lens focal plane and a ray drawn through the center of this lens and parallel to ray 2,3. The intersection of ray 3,4 with the optical axis defines the secondary focal point F_s, and the intersection of ray 3,4 with an extension of ray 1,2 defines a point in the secondary principal plane, SPP.

From point 5, a ray is now drawn to point 6, parallel to the optical axis. The camera lens refracts the ray through its focal point to point 7. Then the auxiliary lens refracts the ray through point 8 toward the optical axis. The same procedure was used to construct point 8 as was used to construct point 4. The intersection of ray 7,8 with the optical axis defines the primary focal point F_p, and the intersection of ray 7,8 with ray 1,2 defines a point in the primary principal plane, PPP.

A part of the construction rays of figure 11(a) which are centered around the camera lens is shown in figure 11(b) to facilitate the derivation of relationships between the two lenses and the single-lens equivalent. The following two relationships are apparent:

$$\frac{f_a}{c} = \frac{f_s}{h_s} \tag{A1}$$

$$\frac{f_c}{c} = \frac{h_s - f_s - f_c}{h_s} \tag{A2}$$

APPENDIX

Solving equation (A1) for the distance h_s yields one of the desired results

$$h_s = \frac{f_s}{f_a} c \tag{A3}$$

Solving equation (A2) for the secondary focal length f_s and substituting equation (A3) for h_s yields the other desired result

$$f_s = \frac{f_a f_c}{c - \left(f_a + f_c\right)} \tag{A4}$$

If the construction rays of figure 11(a) which are centered around the auxiliary lens were similarly investigated, then the following relationships would also become apparent:

$$h_p = \frac{f_p}{f_c} c \tag{A5}$$

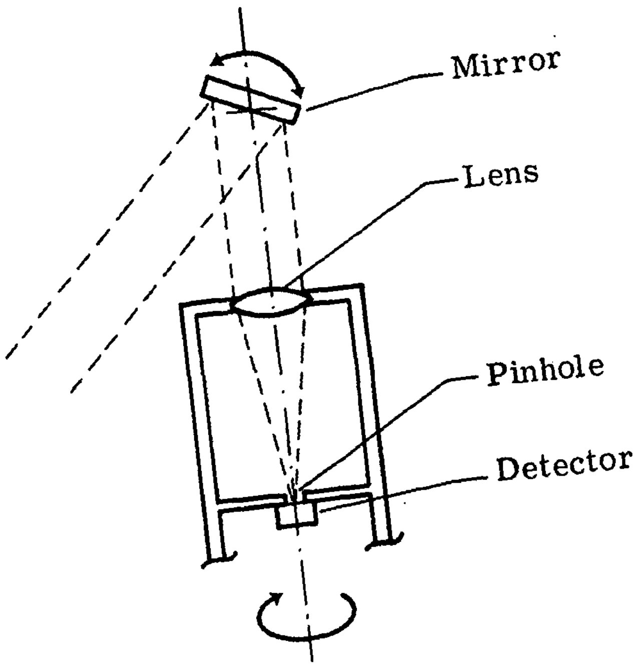
$$f_p = \frac{f_a f_c}{c - \left(f_a + f_c\right)} \tag{A6}$$

Comparing equations (A4) and (A6) shows that $f_s = f_p$.

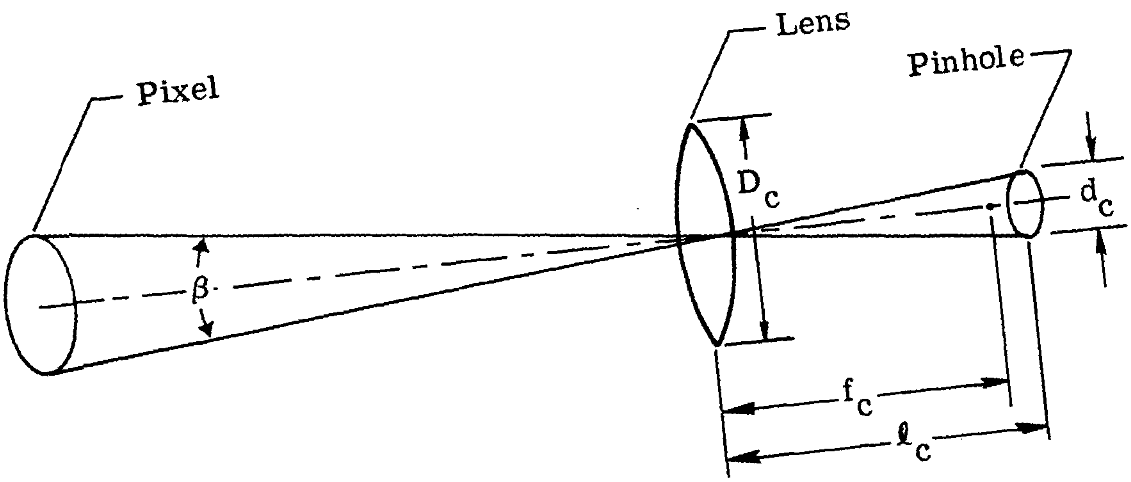
By using the foregoing equations, the single-lens equivalent of the quasi-microscope can be constructed as shown in figure 11(b). It may be noted that the light appears to be emitted from the image and to be incident on the object. This does not, however, limit the use of the single-lens equivalent in any way.

REFERENCES

1. Selivanov, A. S.; Govorov, V. N.; Titov, A. S.; and Chemodanov, V. P.: Lunar Station Television Camera. Contract NAS 7-100, Reilly Translations, 1968. (Available as NASA CR-97884.)
2. Cherkasov, I. I.; Kemurdzhian, A. L.; Mikhaylov, L. N.; Mikheyev, V. V.; Morozov, A. A.; Musatov, A. A.; Savenko, I. A.; Smorodinov, M. I.; and Shvarov, V. V.: First Panoramas of "LUNA-13" – Determination of Density and Mechanical Strength of Lunar Surface Layer at the Landing Site of the Automatic Station "LUNA-13." NASA CR-88874, 1967.
3. Brereton, R. G.; Burke, J. D.; Coryell, R. B.; and Jaffe, L. D.: Lunar Traverse Missions. JPL Quart. Tech. Rev., vol. 1, no. 1, Apr. 1971, pp. 125-137.
4. Surveyor Project Staff: Surveyor Project Final Report. Pt. I. Project Description and Performance, Vol. II. Tech. Rep. 32-1265 (Contract No. NAS 7-100), Jet Propulsion Lab., California Inst. Technol., July 1, 1969.
5. Mutch, T. A.; Binder, A. B.; Huck, F. O.; Levinthal, E. C.; Morris, E. C.; Sagan, Carl; and Young, A. T.: Imaging Experiment: The Viking Lander. Int. J. Solar Syst. Stud., vol. 16, no. 1, Feb. 1972, pp. 92-110.
6. Space Science Board: Planetary Exploration 1968-1975. Nat. Acad. Sci.-Nat. Res. Counc., July 1968.
7. Huck, Friedrich O.; and Lambiotte, Jules J., Jr.: A Performance Analysis of the Optical-Mechanical Scanner as an Imaging System for Planetary Landers. NASA TN D-5552, 1969.
8. Greene, V. W.; Lundgren, D. A.; Mullin, D. D.; and Peterson, R. E.: Microscopic System for Mars Study Program. Rep. 2326 (JPL Contract 950123), Electron. Div., Gen. Mills, Inc., Aug. 30, 1962. (Available as NASA CR-51538.)
9. Loomis, Alden A.: A Lunar and Planetary Petrography Experiment. Tech. Rep. No. 32-785, Jet Propulsion Lab., California Inst. Technol., Sept. 1, 1965. (Available as NASA CR-64917.)
10. Soffen, Gerald A.: Extraterrestrial Optical Microscopy. Appl. Opt., vol. 8, no. 7, July 1969, pp. 1341-1348.
11. Katzberg, Stephen J.; Huck, Friedrich O.; and Wall, Stephen D.: An Investigation of Photosensor Aperture Shaping in Facsimile Cameras. NASA TN D-6882, 1972.
12. Southall, James P. C.: Mirrors, Prisms and Lenses. Third ed., Macmillan Co., c.1933.

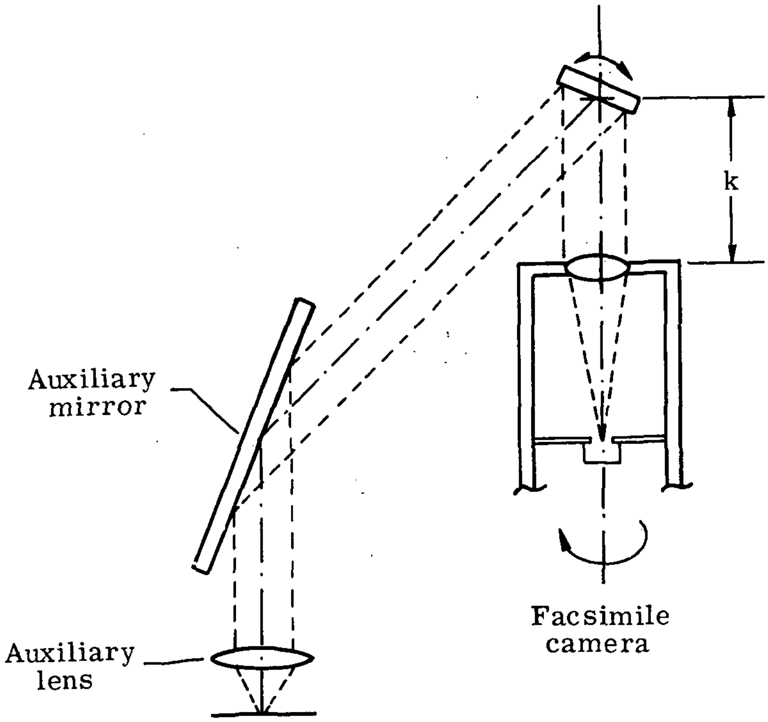


(a) Basic configuration.

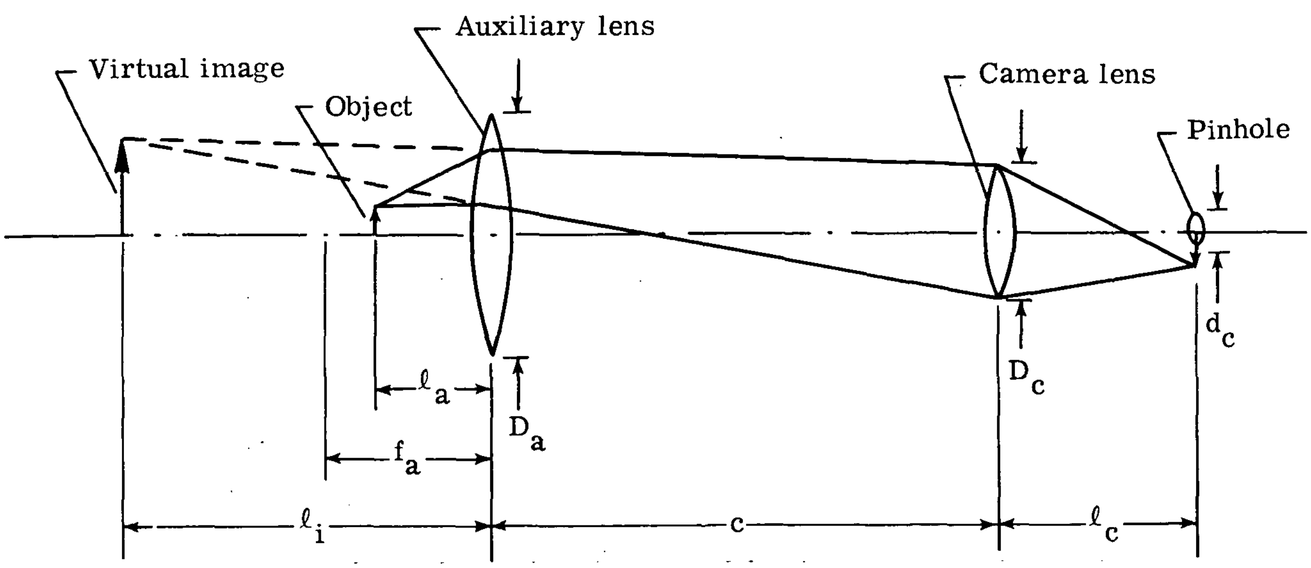


(b) Optical geometry.

Figure 1.- Facsimile camera.



(a) Basic configuration.



(b) Optical geometry.

Figure 2.- Quasi-microscope.

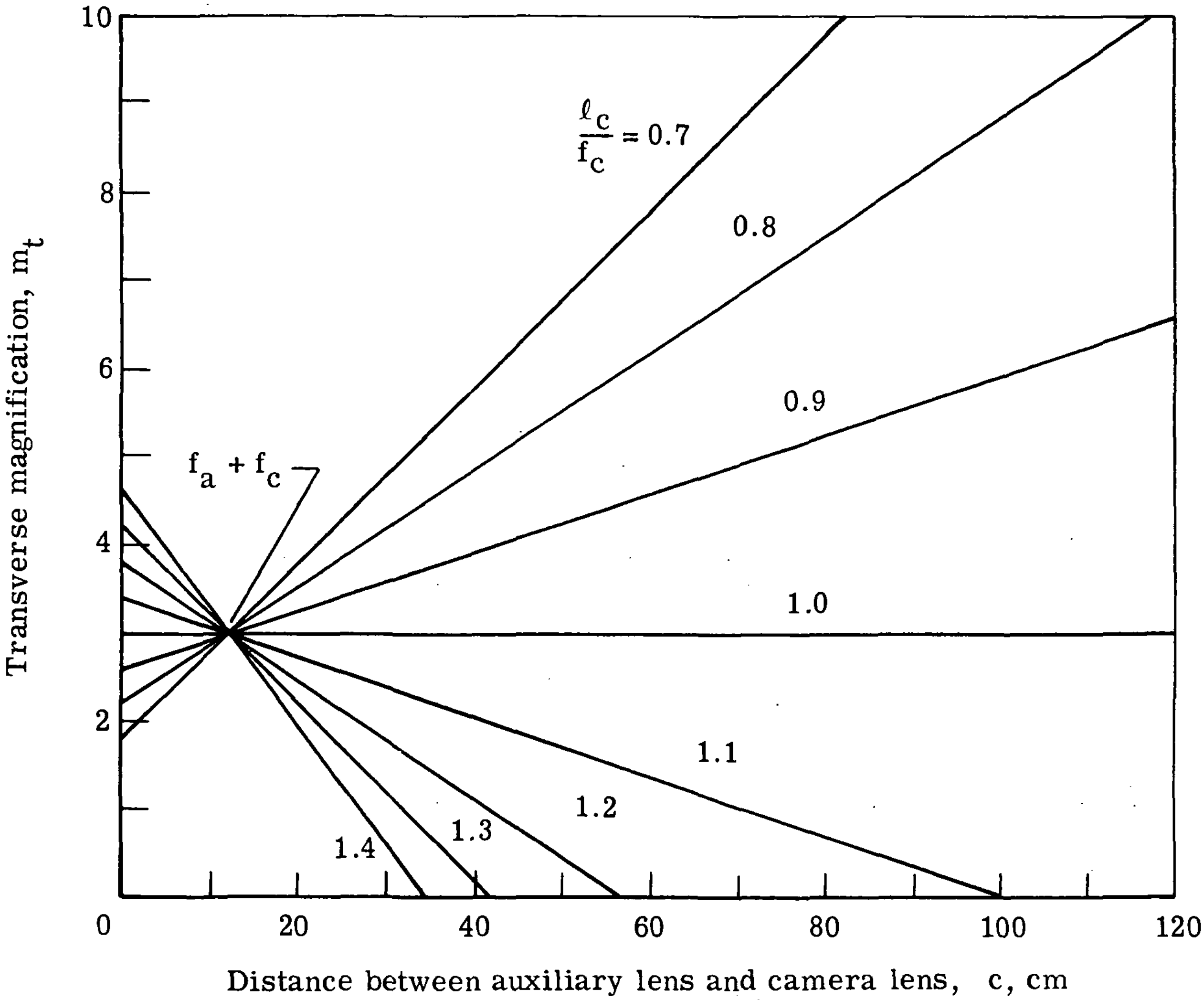
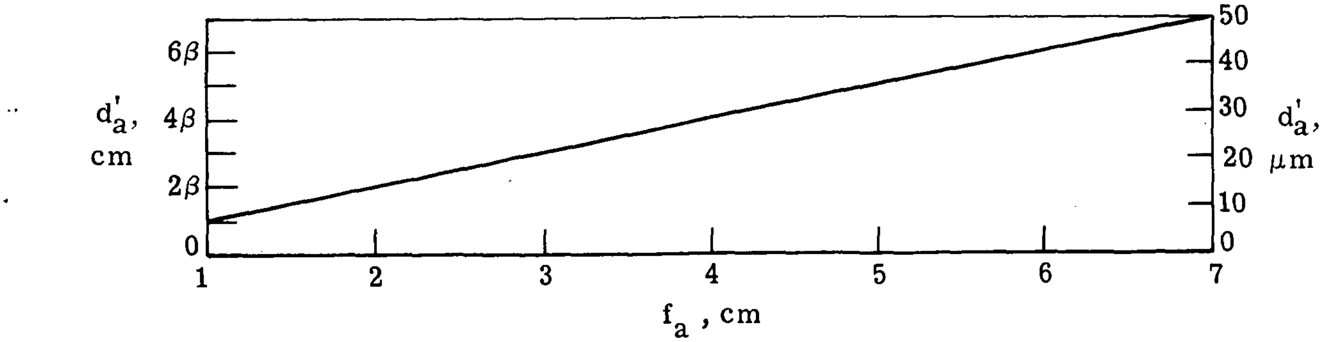
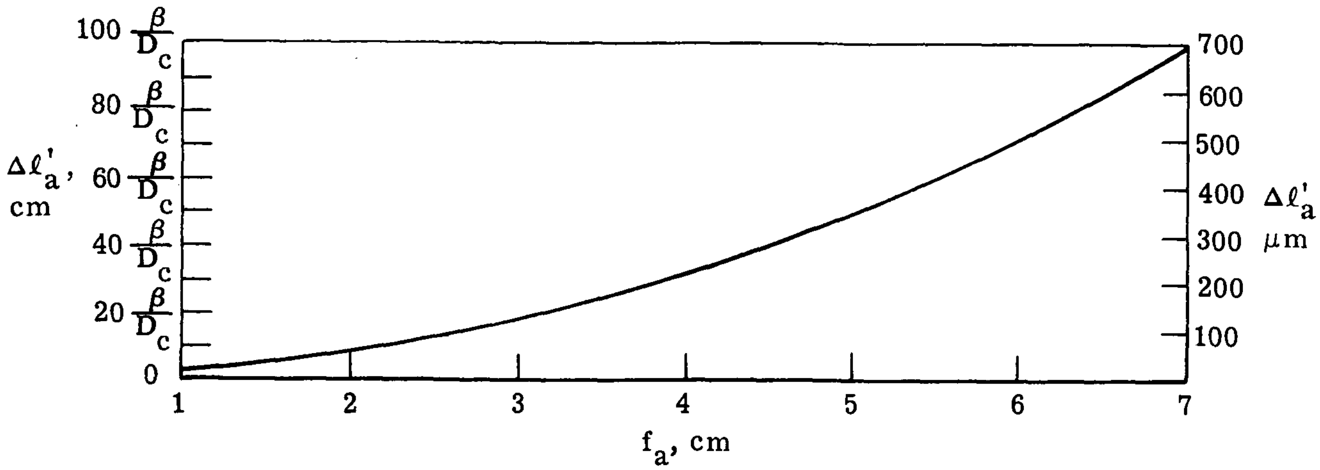


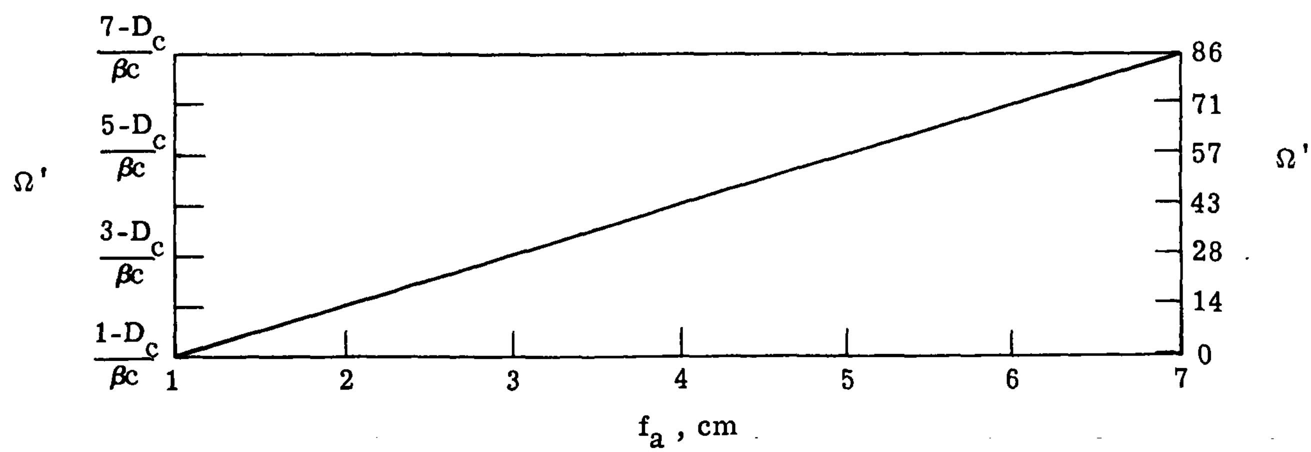
Figure 3.- Variation of transverse magnification with distance between camera lens and auxiliary lens for different values of ℓ_c/f_c.



(a) Resolution.

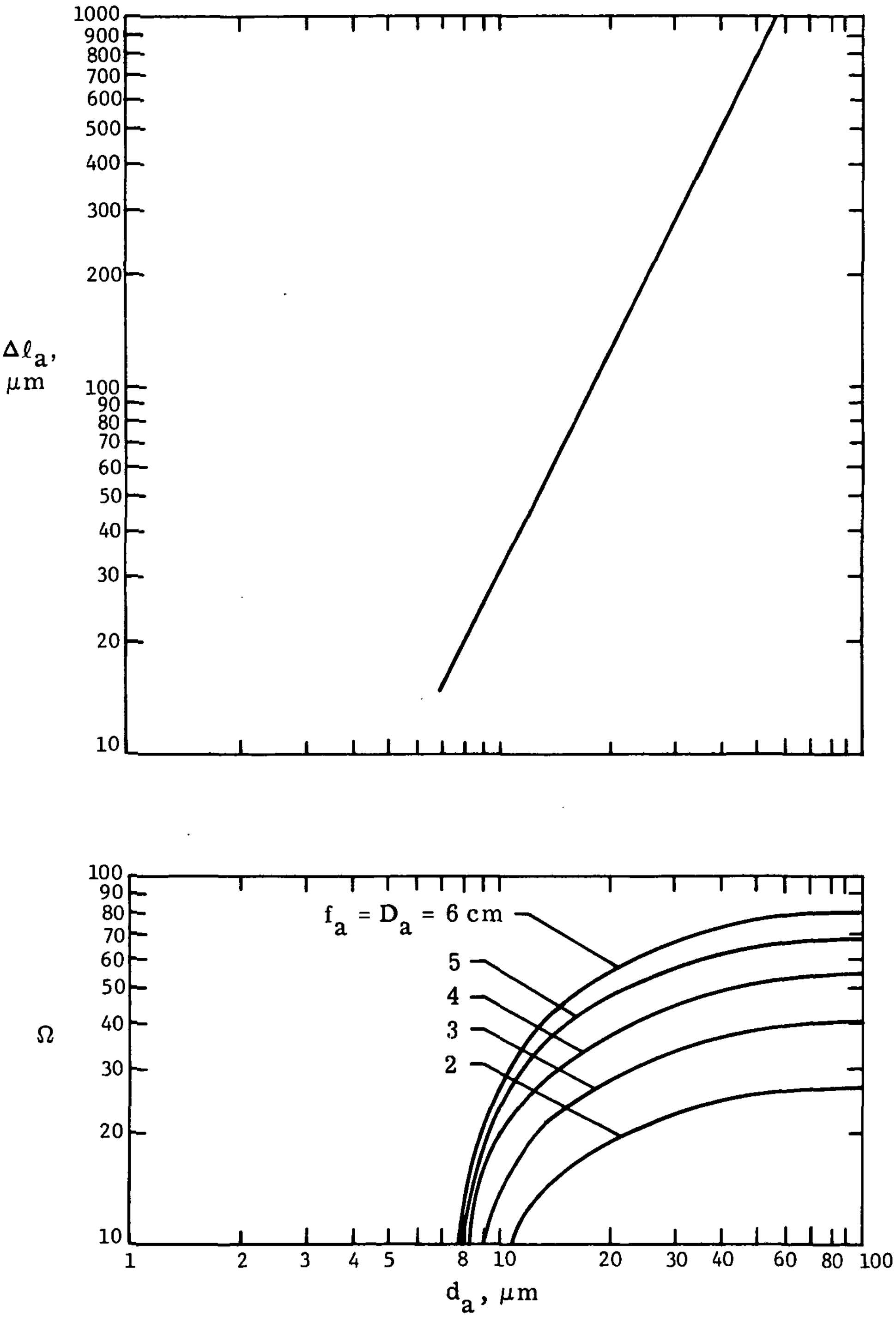


(b) Depth of field.



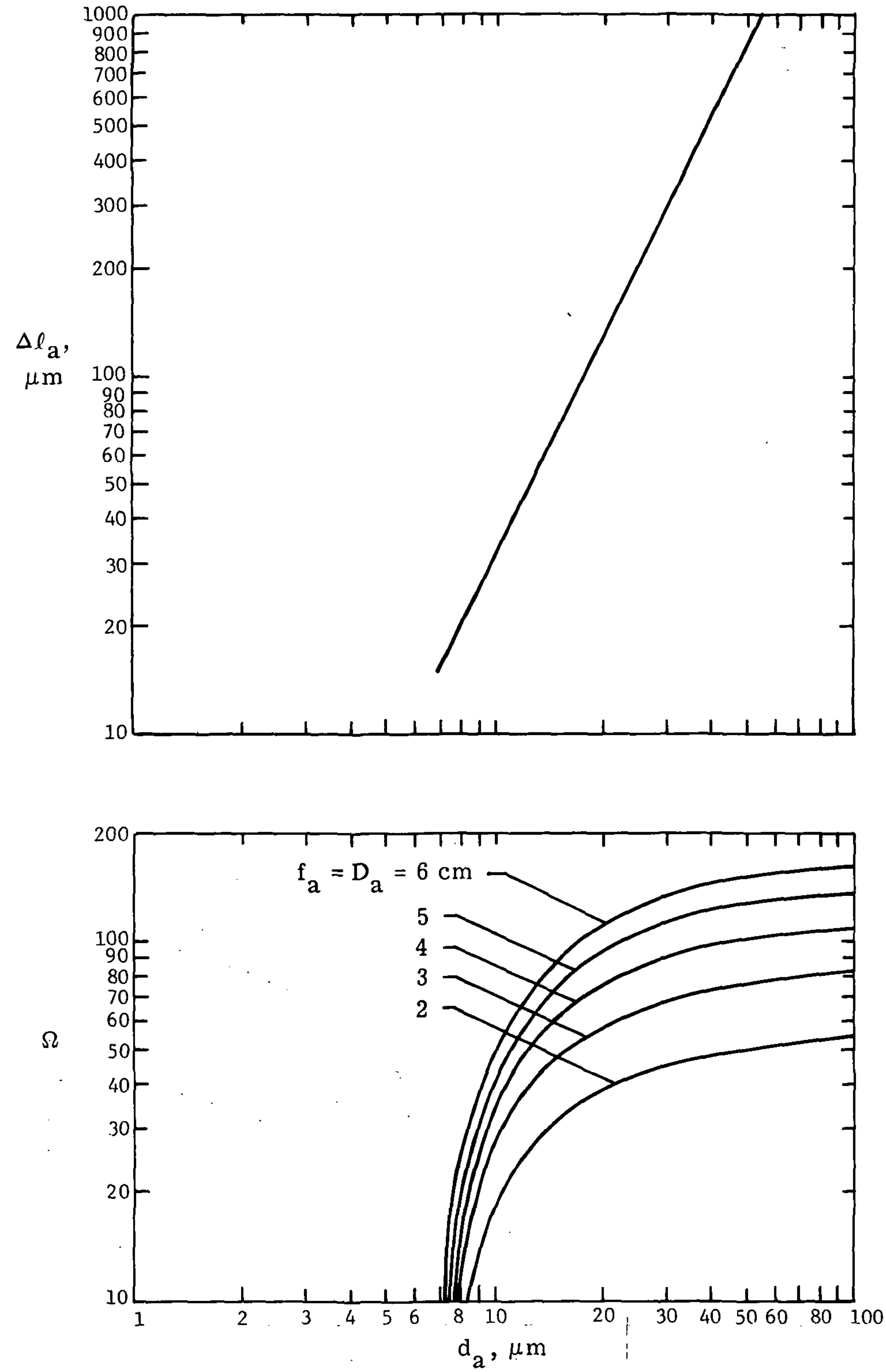
(c) Maximum number of unvignetted pixels per line scan across center of auxiliary lens.

Figure 4.- Quasi-microscope performance when $\ell_a = f_a = D_a$ and $\ell_c = f_c$. Right-hand ordinate values are for Viking lander camera and $c = 100$ cm.



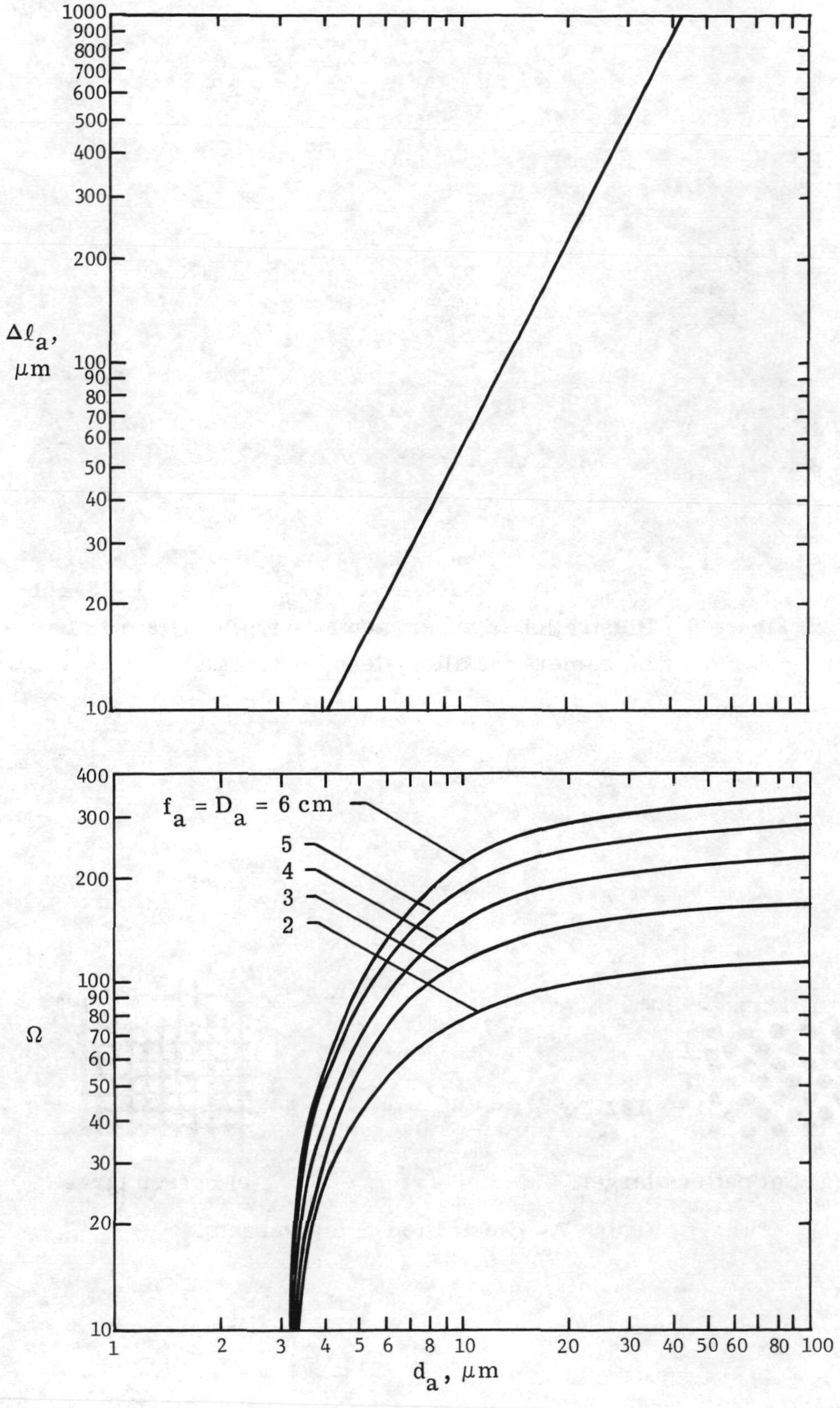
(a) $\beta = 0.04^o$; c = 100 cm.

Figure 5.- Variation with resolution of depth of field and number of unvignetted pixels per line scan across center of auxiliary lens. Camera is assumed to have freedom of focus. Camera lens parameters are $D_c = 0.95$ cm and $f_c = 5.3$ cm.



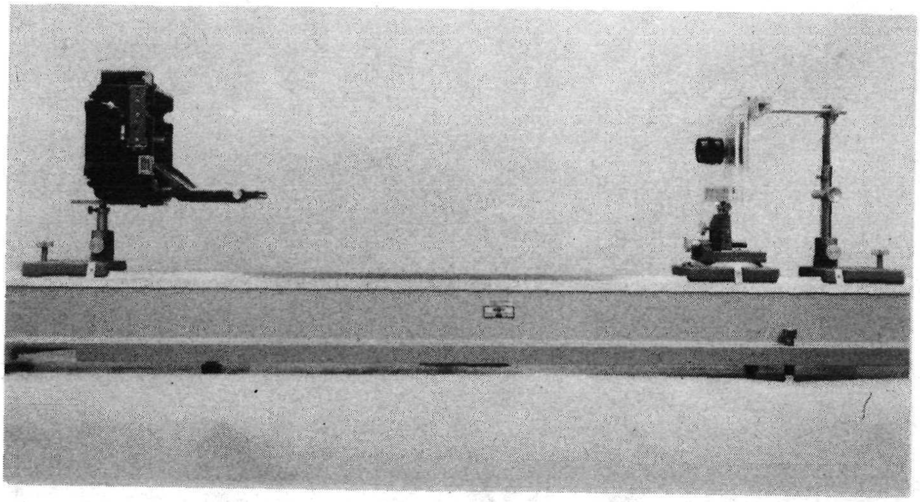
(b) $\beta = 0.04^o$; c = 50 cm.

Figure 5.- Continued.



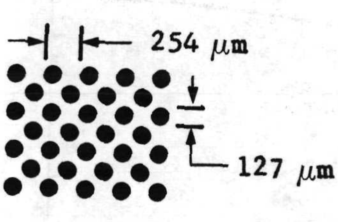
(c) $\beta = 0.02^{\circ}$; c = 50 cm.

Figure 5.- Concluded.

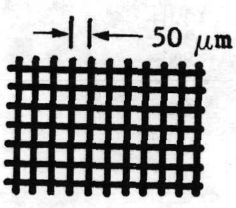


L-73-211

Figure 6.- Illustration of experimental setup, consisting of film camera, auxiliary lens, and target.

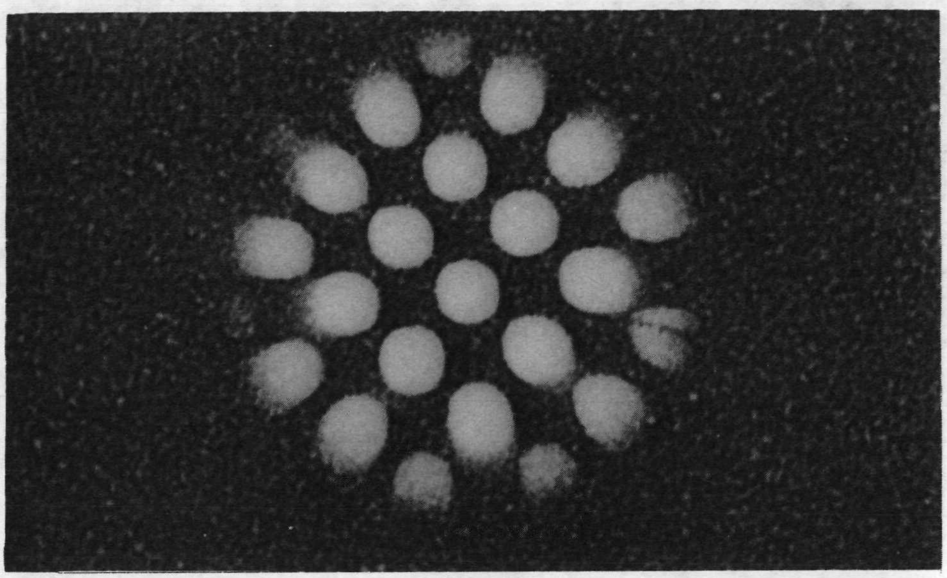


(a) Dot pattern target.

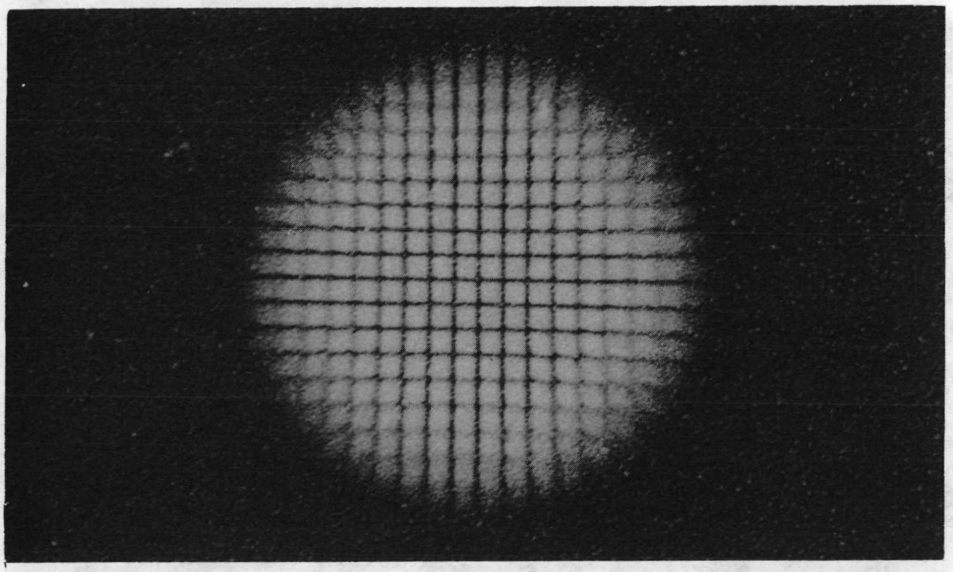


(b) Screen target.

Figure 7.- Illustration of test targets.



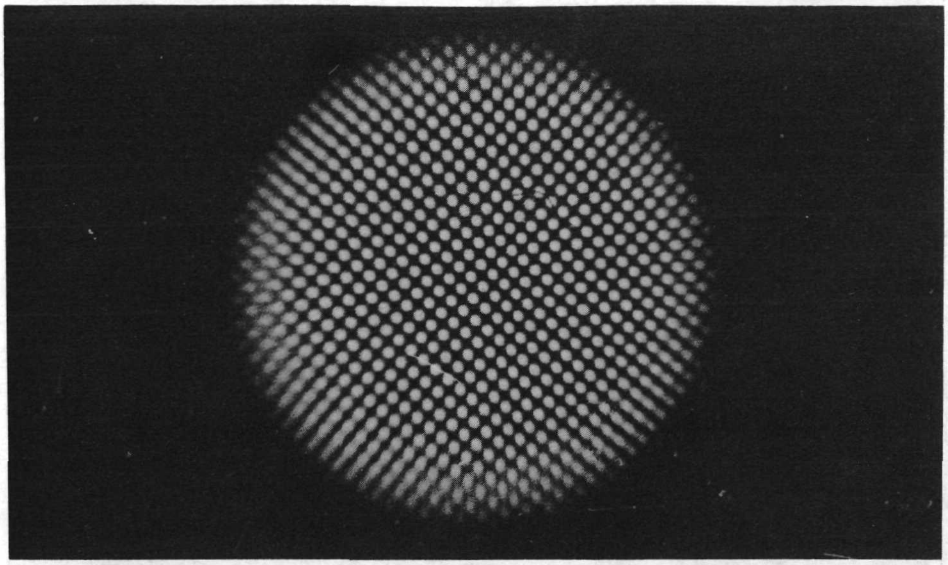
(a) Dot pattern target.



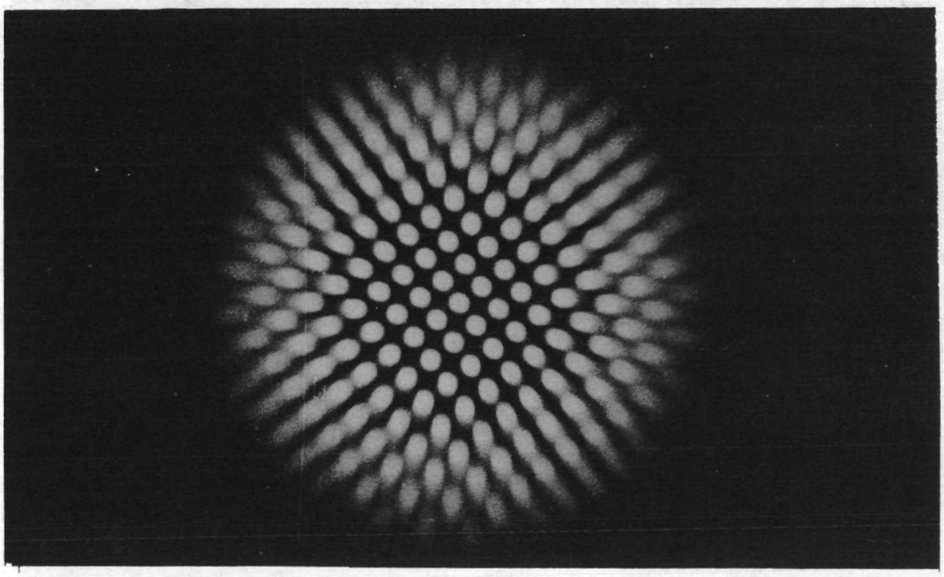
L-73-212

(b) Screen target.

Figure 8.- Quasi-microscope images obtained with the 2.5-cm focal length (f/0.78) auxiliary lens. The targets are located at focal point of auxiliary lens and the camera is focused at infinity.



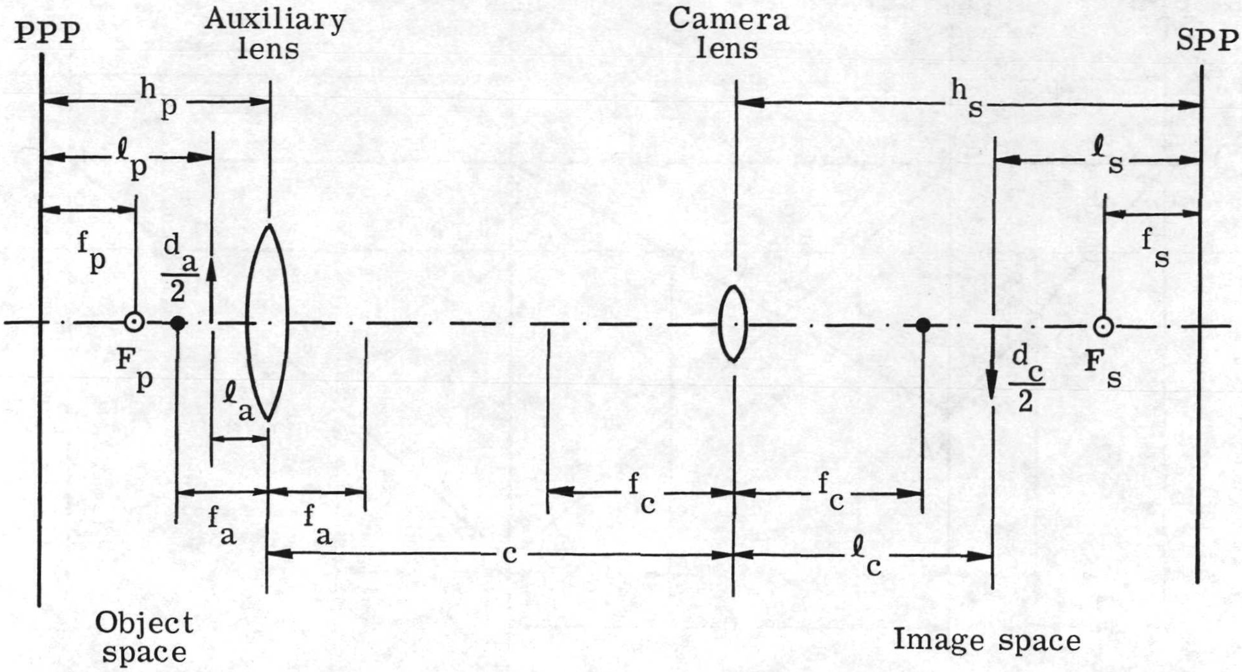
(a) Dot pattern target is located at focal point of auxiliary lens and the camera is focused at infinity.



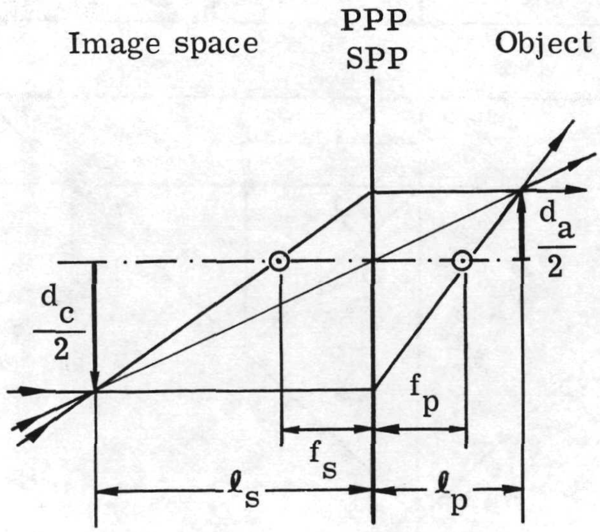
L-73-213

(b) Dot pattern target is located 6.8 cm from auxiliary lens and the camera is focused beyond infinity.

Figure 9.- Quasi-microscope images obtained with the 6.5-cm focal length (f/0.78) auxiliary lens.



(a) Quasi-microscope optical geometry.



$$f = f_p = f_s$$

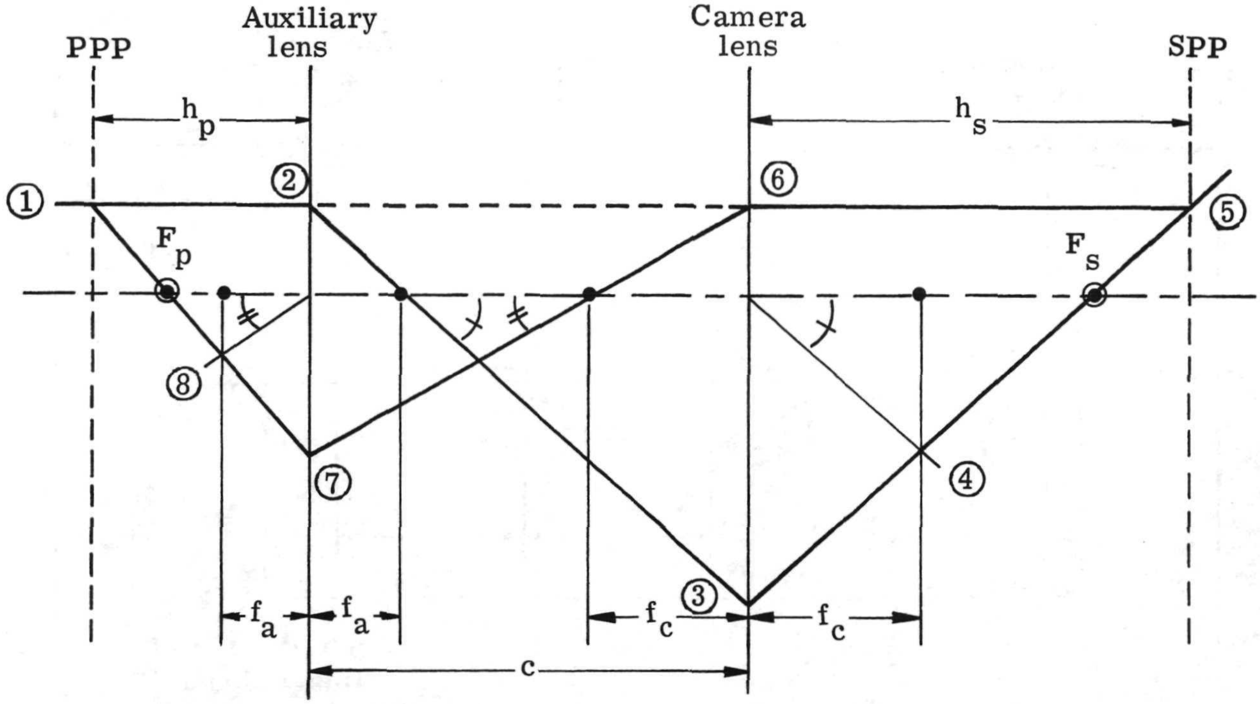
$$h_s = \frac{f}{f_a} c$$

$$h_p = \frac{f}{f_c} c$$

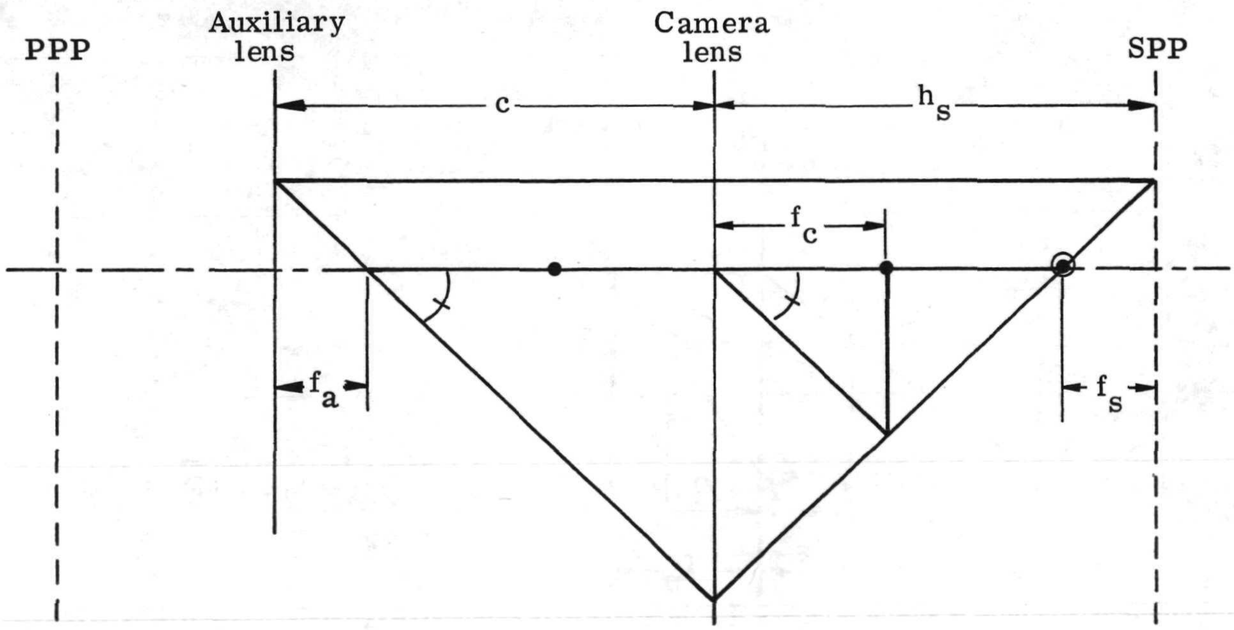
$$f = \frac{f_a f_c}{c - (f_a + f_c)}$$

(b) Single-lens equivalent.

Figure 10.- Single-lens equivalent of quasi-microscope.



(a) Construction of primary and secondary principal planes PPP and SPP, and determination of primary and secondary focal points F_p and F_s.



(b) Illustration of geometrical relationships for determining distance h_s and the secondary focal length f_s.

Figure 11.- Geometry for deriving single-lens equivalent of two lenses.

NASA-Langley, 1973 — 14 L-8527

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546